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Design and Performance of the Cryogenic Flexible Diode Heat Pipe (CRYOFD) Flight Experiment

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Space & Aeronautics Technology Division
1900 Randolph Road SE
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Design and Performance of the Cryogenic Flexible Diode Heat Pipe (CRYOFD) Flight Experiment

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ABSTRACT

The first space flight cryogenic flexible diode heat pipes (CFDHPs) were developed and verified under micro-gravity conditions on the Space Shuttle during STS-94 (July 1997) and the previous, minimum mission STS-83 (March 1997). The heat pipe working fluids were oxygen (with an operating range of 60 to 145 Kelvin) and methane (95 - 175 Kelvin). The heat pipes were verified as part of the Cryogenic Flexible Diode Heat Pipe (CRYOFD) flight experiment. CRYOFD was the third and fourth flights of the Hitchhiker based Cryogenic Test Bed (CTB). CRYOFD was managed by the Air Force Research Laboratory (AFRL) Phillips Research Site with NASA's Goddard Space Flight Center (GSFC) co-sponsoring the experiment, the Air Force's Space Test Program (STP) and GSFC's Hitchhiker (HH) group provided the Shuttle integration and support. Jackson and Tull (J&T) and Swales Aerospace, Inc. (SAI) executed the program as a Phase II SBIR under the AFRL. Additional Support was provided by Aerospace Corporation and Nichols Research Corporation.

INTRODUCTION

The primary applications for cryogenic flexible heat pipe technology are to facilitate integration of cryogenic refrigerators (or cryo-coolers) to space based infrared sensors and to reduce cryo-cooler induced vibration at the focal plane. The flexible section of the heat pipe also helps to accommodate differential thermal contraction and expansion caused by large thermal gradients and/or dissimilar materials with incompatible coefficients of thermal expansion (CTE). The flexible nature of these heat pipes eases the integration of the heat pipe into existing or cramped systems. The diode has applications in isolating a sensor from a redundant or failed cryo-cooler or isolating a sensor from hot transients on a radiator.

The heat pipes provide over 100 times the heat transport capability of equivalent solid conductors and allow minimal temperature drops for transport across significant distances. The flexibility of the heat pipes allows for improved integration and assembly and, if required, on orbit deployment and/or pointing. The diode capability originally was intended to enable the use of a higher temperature cryogenic radiator as an alternate cooling source to the primary cryo-coolers. For a larger set of applications, the diode capability also provides for the minimization of redundant or "off" cryo-cooler parasitic heat loads.

Overall, the CRYOFD was the first flight of cryogenic flexible diode heat pipes, only approximately the fifth flight of cryogenic heat pipes, and the flight of the highest capacity oxygen and methane heat pipes to date.

EXPERIMENT DESCRIPTION

In 1990 Jackson and Tull and OAO Thermal Systems developed the Cryogenic Test Bed (CTB) as a joint NASA/GSFC and USAF/AFRL test platform for testing cryogenic multiphase thermal components.[1, 2, 3] The CRYOFD is the third (and fourth) flight of the CTB.

The CTB has been developed to provide a platform for quick turnaround of cryogenic flight demonstrations. The CTB consists of two electronics boxes, the Power Distribution Box (PDB) and the CTB Experiment Control Module (CECM). The cooling of the flight test articles is provided by five tactical cryogenic refrigerators (three on the Oxygen Flexible Diode Heat Pipe (OFD) side and two on the Methane Flexible Diode Heat Pipe (MFD)). Figure 1 shows the heat pipes installed in the CTB structure.

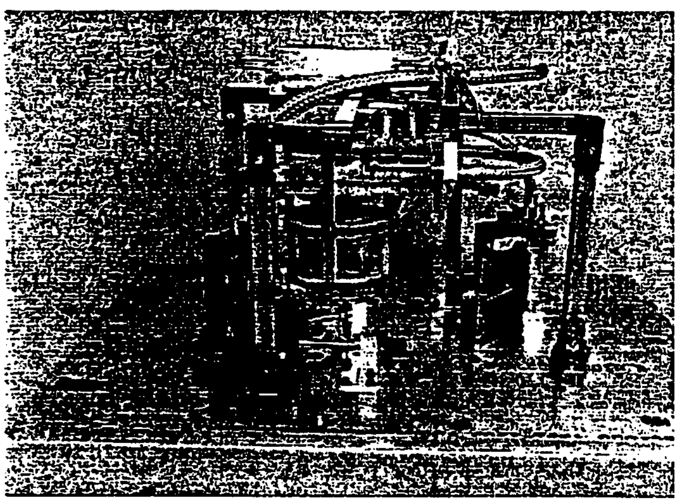


Figure 1 Heat Pipes Installed in CTB Structure

CRYOGENIC FLEXIBLE DIODE HEAT PIPES - The CFDHPs are illustrated in Figures 2 and 3. Each unit consists of Hastelloy C high strength steel tubing at the evaporator and condenser ends that is welded to 316L stainless steel flexible bellows hose. The hose is over-wrapped with stainless steel (SS) double braid to provide adequate pressure containment. The evaporator and condenser sections are threaded internally to provide circumferencial distribution of the working fluid. The CFDHPs incorporate a circular woven SS wick structure through their entire length. A 316L SS reservoir is welded to the evaporator end of the heat pipe and aluminum saddles are soldered to both the evaporator and condenser ends of the heat pipe. The liquid trap consists of two hemispherical end caps welded to a cylinder. An SS wire cloth (200 mesh) wrapped cylindrical core is installed inside the reservoir to "trap-out" liquid and prevent reverse heat piping. The traps are sized to accommodate all of the working fluid with 20% excess. Oxygen is used as the cryogenic working fluid in the OFD, and methane is used as the cryogenic working fluid in the MFD. The Thermal Storage Unit (TSU) phase change material (PCM) canister that was previously flown in CRYOTP[4] is thermally coupled to the MFD's evaporator and liquid trap. When the heat pipe shuts down during diode reversal, the melting of the PCM at 120 K permits the TSU to store the heat pipe's transient shutdown energy and parasitic heat flows due to conduction or radiation. Temperature control at 120 K is maintained until all of the PCM is melted (~2500 Joules of energy) at which time the TSU will rise in temperature at a rate consistent with its thermal mass and the prevailing heat leaks. An aluminum thermal mass is used with the OFD to provide energy storage during reversal but with an attendant rise in temperature.

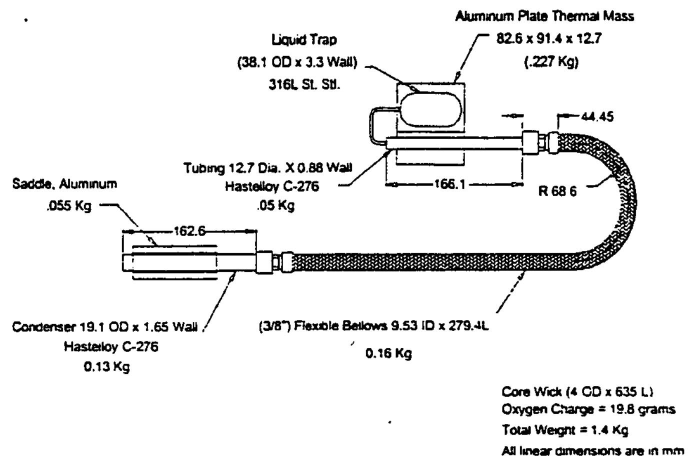


Figure 2 OFD Design

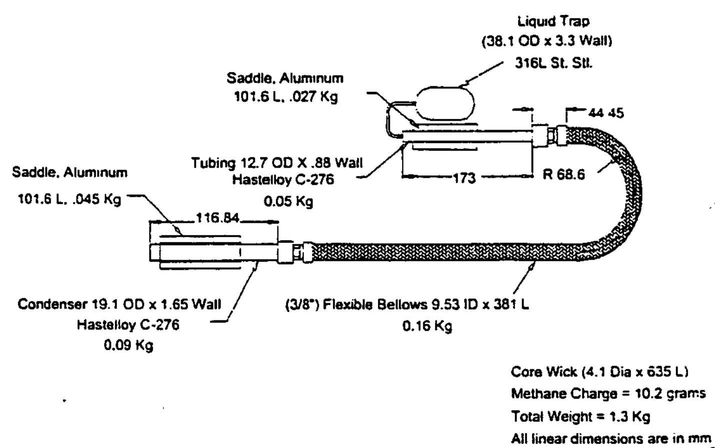


Figure 3 MFD Design

The MFD was designed to operate over the range of 100 to 170 K. It is charged with 10.2 grams of methane which represents 5,080 Joules (1.41 W-hr) of energy that must be accommodated during the diode's shutdown at 120 K. The corresponding Maximum Design Pressure (MDP) at 353 K (80°C) is 119.6 bars for this unit. It is thermally connected to two of the cryo-coolers using a copper braided interface coupling. The OFD is similarly interfaced with the remaining three cryo-coolers which are needed to accommodate its lower operating temperatures range (e.g. 60 – 145 K). Its fluid inventory is 19.8 grams which corresponds to 4,000 Joules (1.11 W-hr) of shutdown energy at 100 K. The OFD's corresponding MDP is 144.4 bars at 353 K (80°C). Each of the subassemblies is integrated into the CTB as is illustrated in Figure 4.

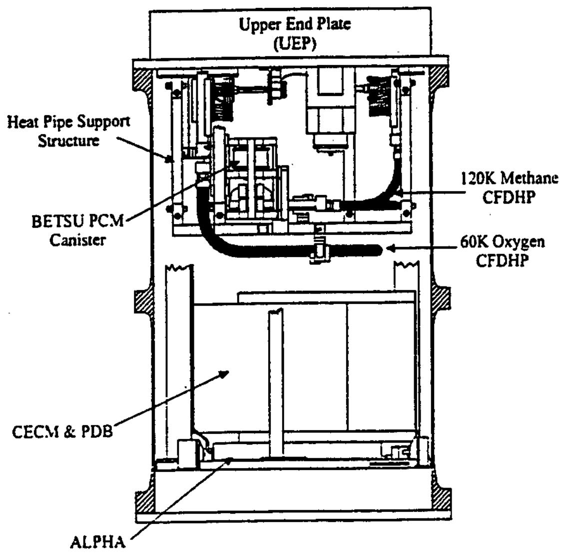
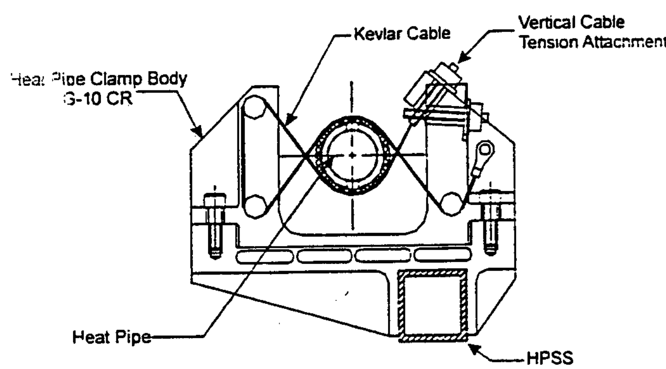


Figure 4 CTB Integration

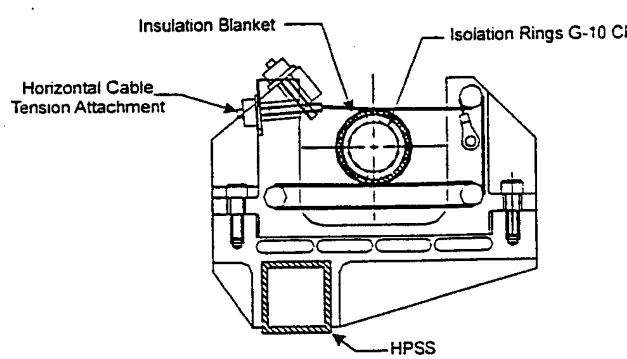
Note that once integrated each of the configurations are three-dimensional. Hence only reflux operation was verified after installation into the test bed. The units are isolated from the support structure using Kevlar straps and G-10 brackets as shown in Figure 5. This technique is identical to the isolation provided in the previous flight experiments.[5,6]

Special features that are incorporated into each of the CFDHPs are a composite wick structure for increased transport, a large diameter condenser section to facilitate startup, and offset fittings that interface the condenser and evaporator section with the flexible section. This last feature was used to center the core wick with the bellows diameter while permitting it to rest on the bottom of the evaporator and condenser tubes to facilitate startup in 1- g. The larger diameter condenser (e.g. 19.1 mm vs 12.7 mm evaporator OD) was used to ensure that all of the liquid could be condensed within the condenser section to insure startup.[7] Reduction of the pressure to subcritical (which is also necessary to guarantee startup[7]) was insured by the additional containment volume of the liquid trap and the flexible bellows, and the larger volume of the condenser.

The composite wick consists of woven fibrous core that is over-wrapped with fine 400 wire mesh wick material and then secured with another outer-wrap of 400 mesh screen that is secured with another outer wrap of 400 mesh screen that is sealed by spot-welding over the length of the wick. Its effective pumping radius is about twice ideal as measured by hydrostatic bubble test and is approximately equal to that of 200-mesh screen. The larger pore size is due primarily to imperfections in the 400-mesh screen. A stainless fitting seals the wick at the evaporator end. The core wick consists of .15 mm wire diameter woven wire mesh that has an 80% porosity. This wick has a reasonably good permeability and effective pumping radius and its non-composite transport capability is used to prime the wick during transient cool down. Once primed the pumping derived from the effective pore size of the fine mesh outer wrap increases the transport of the wick. As a result the primed or composite transport capability of this design is approximately 3.5 times greater than that of the homogeneous core. This allows the wick area to be reduced for a given transport requirement which in turn reduces the fluid inventory and the associated pressure containment required and the amount of energy back flow that is required for diode shutdown.



This View Shows Only Vertical Wire Constraint



This View Shows Only Horizontal Wire Constraint

Figure 5 Heat Pipe Attachment and Isolation Supports

THERMAL STORAGE UNIT (TSU) - The TSU was flown previously as part of CRYOTP on the Office of Advanced Science and Technology –2 (OAST-2) bridge on STS-62 in 1994.[4] The phase change material (PCM) is approximately 35 grams of 2-methylpentane (doped with 3% acetone), to provide 2,500 Joules of energy storage at a freeze/thaw temperature of 120 K. The acetone minimizes the sub-cooling effects and thereby provides a more precise freeze point and more stable temperature control. Table 1 provides a design summary of the TSU.

Table 1 Design Summary for TSU Canister

Phase Change Material	2-methylpentane & 3% acetone
Theoretical Capacity Available	2,500 Joules
Maximum Pressure at 80°C	3.81 Bars
Nominal Void Volume at 120 K	33%
Maximum ΔT in PCM @ 1w	0.3 K
Volume Percent Metal Fin	24%
Inside Diameter	61 mm
Inside Length	29 mm
L/D	0.48
PCM Mass	35.3 grams
Canister Total Mass	136 grams
Canister Wall Thickness	0.254 mm
PCM to Wall Conductance Ratio	18
PCM to Fin Conductance Ratio	16
Fin Thickness	0.2 mm
Fin Density, Fins per mm	1.19
Canister Material	6061-T6 Aluminum
Fin Material	3003-0 Aluminum

INSTRUMENTATION - Two kapton foil heaters (one 15 W and one 7.5 W) and their tri-series bi-metallic thermostats are epoxied to the saddles at the evaporator and condenser sections. In the case of the MFD, the 7.5 W evaporator heater is located on the topside of the BETSU to permit testing of the BETSU. The MFD/BETSU effectively simulates a potential cryogenic bus application where excess heat from a sensor will melt the phase change material, which is subsequently frozen as heat is removed by the CFDHP to a cryogenic cooler system. The heaters at the condenser ends are used to provide temperature control during transport tests. The evaporator and condenser heaters are commanded to 16 discrete power levels (including 0 watts), which permit incremental 0.5 watt heat inputs from 0 to 7.5 watts and 1.0 watt increments from 0 to 15 watts. The maximum power that can be applied for transport tests is 22.5 watts. There are also two independent primary and redundant foil heaters on each liquid trap. These are discrete 5 watt heaters that can be used to facilitate restart from a diode shutdown mode.

The MFD/BETSU system has a total of 14 platinum resistance thermometers (PRTs) for temperature measurements, and the OFD has 12 PRTs. Housekeeping and other ambient temperature data are derived using a total of 26 thermistors located throughout the experiment.

INSULATION - Each unit is gold plated and wrapped in multi-layer insulation (MLI) thermal blankets, and additional MLI thermal blankets were wrapped around the cold portions of the test bed.

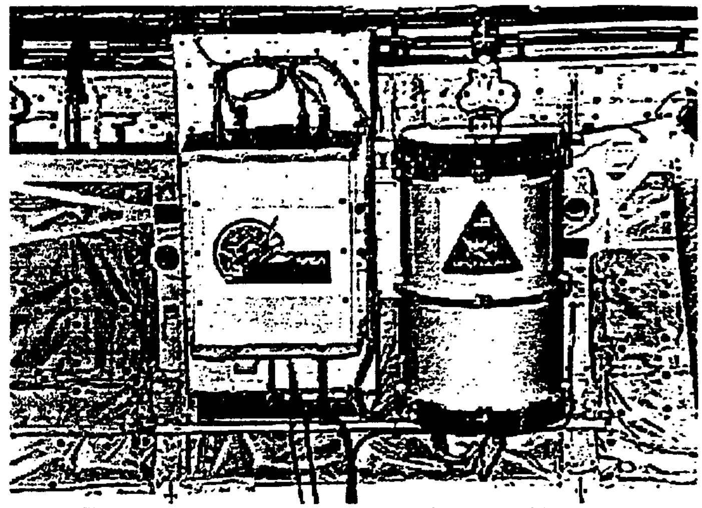


Figure 6 CRYOFD Installed in the Shuttle

OPERATIONS

Ground operations consisted of vibration testing and proof pressure cycling followed by burst pressure testing with qualification units. All results were nominal with no failures and minimum burst factors of safety well above the 4.0 design criterion. A small number of thermal vacuum tests were conducted with the flight articles due to limited schedule. Dryout of the MFD occurred between 16 and 18 watts of heater power at 106 K at an adverse tilt of 25.4 mm. Dryout of the OFD occurred between 5 and 6.2 watts of heater power at 75 K at an adverse tilt of 25.4 mm. Both results show good agreement with their theoretical performance (See Figures 8 and 11). Thermal vacuum tests were also conducted at the system level with the CFDHPs in a reflux orientation. These tests demonstrated ground startup.

Flight operations consisted of individual transient cool-down and startup tests with each unit. Once cooled to the desired operating temperature, heat was applied to the evaporator and increased incrementally every 10 to 15 minutes until dryout or transient run-away of the evaporator was obtained. Steady-state dry outs at the lower end of the respective operating temperature ranges could not be obtained due to the insufficient cryo-cooler capacity at lower temperatures. In these cases the heat loads were increased until dryout was observed as the operating temperature also increased.

Diode shutdown with each unit was also tested by turning off the cryo-cooler and in some cases applying heater power at the condenser. Restart from a shutdown condition was also demonstrated. Faster restart was observed by applying heat to the liquid trap to drive the fluid back into the heat pipe. Freeze/thaw characteristics and temperature control with the TSU were evaluated as part of the MFD forward mode and diode shutdown operations.

FLIGHT RESULTS

Most of the effort during flight was directed toward determining the transient startup, the transport capacity and the diode operation of the heat pipes. Steady state transport test operation was difficult to obtain due to the limited cryo-cooler capacity. Diode shutdown tends to be transient but is aggravated by the parasitic heat leaks to the heat pipes, which further affect the transient. Parasitic losses were relatively high, and increased with the duration of the experiment. This was due to the heating up of the Hitchhiker (HH) canister and reduced cooling capacity of the cryo-coolers as the radiating upper end plate (UEP) got warmer. The transient nature of the UEP temperature and its resultant effect on the coolers' performance made it somewhat subjective to determine the exact power at which dryout occurred. In the data reduction, dryouts were declared at the point at which evaporator and condenser temperatures began to diverge and failed to recover (until the heat load was decreased or removed). Diode shutdown was declared under similar conditions (i.e. reversal of the heat pipe gradient), but was much more difficult to ascertain because although the coolers were turned off, ambient heating of the heat pipes dominated the temperature responses of the pipes. Using these constraints the following results were obtained.

METHANE FLEXIBLE HEAT PIPE PERFORMANCE - Figure 7 shows an on-orbit cooldown and priming of the methane heat pipe. Isothermalization of the heat pipe occurred at 155 K approximately 4 hours from the initiation of cooldown. The rapid cooldown and high temperature for isothermalization indicates that the system pressure became subcritical very early in the cooldown with condensation beginning very near the critical temperature. Figure 8 shows the predicted heat pipe capacity versus the flight data including complete and partial dryouts and holding heat loads over transient and steady state conditions. Because of the limited cooler capacity, only a few complete dryouts were obtained and only at the upper end of the operating temperature range of the heat pipe.

All test data has been adjusted to account for parasitic heat inputs due to radiation and conduction. The parasitic heat input to the MFD system occurred primarily at the evaporator end due to conduction from the TSU and liquid trap, with smaller radiative loads on the transport and condenser sections. The net effect of the parasitics on the MFD is to increase the heat load that must be transported by the unit by approximately 4.7 watts at 155 K. This is the amount that must be transported by the non-composite wick structure as it goes through the transient startup prior to being fully primed. The theoretical transport capability of the non-composite core is 3.49 W-m at 155 K. With an effective length of 0.648 m, the maximum theoretical heat load that can be transported is 5.4 watts, which is greater than the estimated parasitics and therefore isothermal startup and full priming at 155 K could be achieved as demonstrated. Higher parasitics would have resulted in isothermalization at a lower temperature.

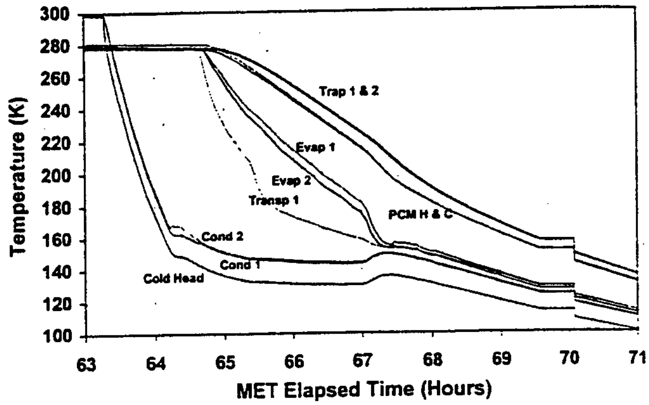


Figure 7 MFD Cooldown and Startup (3 July 97)

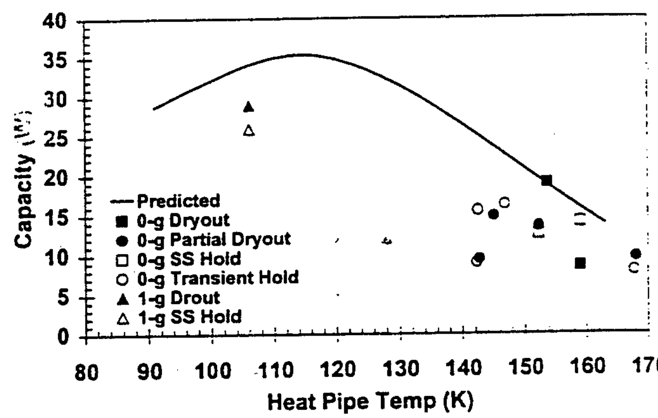


Figure 8 MFD Transport Capacity

The measured test results tend to be 10-20% below theoretical in the flight tests. The fact that steady-state partial dryouts occur is indicative that dryout is occurring in the circumferential threads since a partial dryout cannot exist in the composite core except as a short transient without any possibility of recovery. This is the probable explanation for the difference between actual and theoretical. The transport model is based on the maximum capability of the composite wick and does not take into account the circumferential liquid flow which appears to be defining the transport limit. Increased vapor losses due to the bends or increased liquid losses in the wick due to stretching of the wick in the bends are also possibilities since ground tests were conducted with the pipe straight. Further analysis is necessary to complete the data correlation.

Figure 9 shows an MFD diode reversal at 110 K with 3.5 watts applied to the condenser at MET 86.3 hours, and 5.5 watts at MET 86.4 hours. Close examination of the flight data shows that the condenser rises above the evaporator and trap temperatures at an MET of 86.6 hours, when their temperatures are 128 K. At an MET of 86.7 hours, the condenser is drying out and its temperature begins to rise rapidly above the evaporator temperature, which in turn levels off, indicating that shutdown is complete. The turndown time is a maximum of 9 minutes and the corresponding shutdown energy is estimated to be 1.2 W-hr, which is 85% of the MFD's methane inventory. It should be noted that during this cycle an average of approximately 3.5 watts were being transferred to the TSU as it was melting. This corresponds to 12 minutes of melt time for the 2500 joules of stored energy. A leveling of the PCM, evaporator and trap temperatures can be observed in the transient data as the PCM melts between MET 86.55 and 86.75 hours.

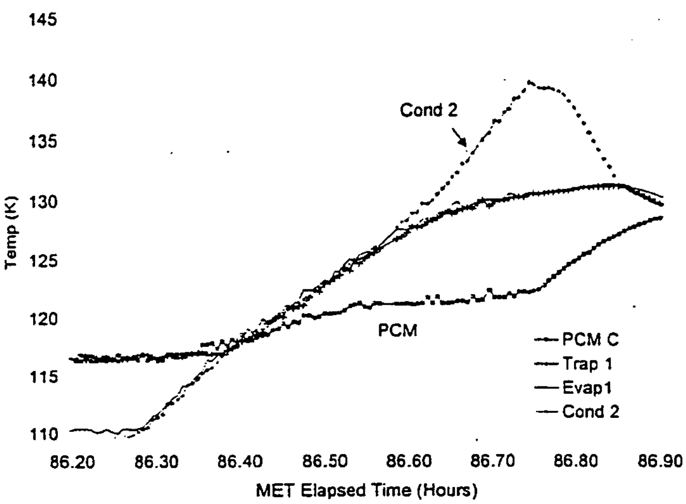


Figure 9 MFD Diode Shutdown

OXYGEN FLEXIBLE HEAT PIPE PERFORMANCE

Figure 10 shows a cooldown and priming of the oxygen heat pipe. Isothermalization occurs at 112 K at approximately four hours from the start of cooldown. Cooldown of the liquid trap lags slightly (1-2 K) due to its high thermal mass and the parasitic heat input. Its isothermalization with the rest of the pipe is not required for forward mode operation.

Figure 11 shows the predicted heat pipe transport capacity compared with the flight and ground test data. It can be seen that it was not possible to verify the capacity below 85 K because of the inability of the cryo-coolers to carry the load. The OFD data shows very good agreement with predicted and in general there is better correlation than with the methane. This would imply along with the ground and flight data for the MFD that the pumping radius may not be as small with the methane composite wick. It is possible that the methane wick could have been damaged during insertion into the heat pipe. The "transient-hold" data for the OFD is provided as reference and only indicates that there was no dryout at these transient heat loads.

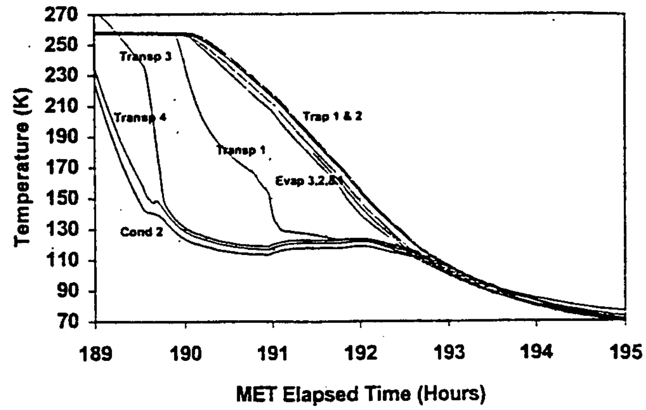


Figure 10 OFD Cooldown and Startup (8 July 97)

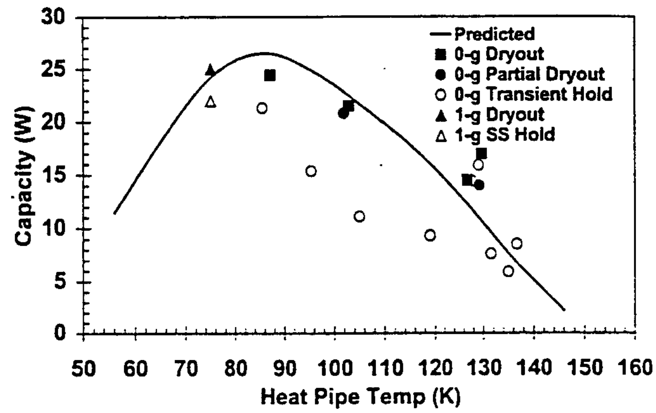


Figure 11 OFD Transport Capacity

Figure 12 shows an OFD diode reversal at 110 K with 3.5 watts applied at the condenser. Complete shutdown occurs in about 8 minutes. The corresponding shutdown energy was estimated to be 1.1 watt-hr which is equivalent to 100% of the oxygen inventory.

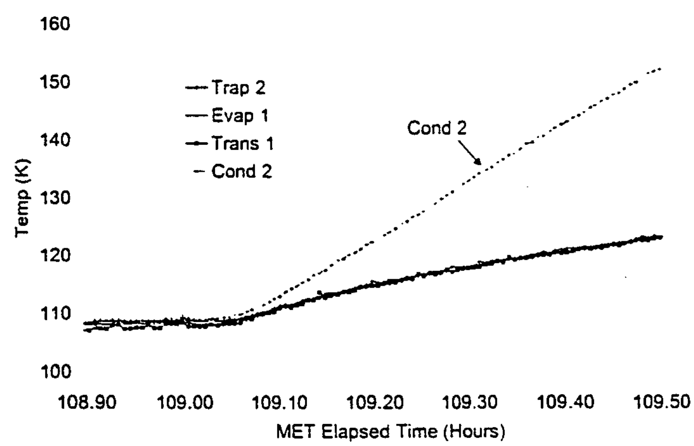


Figure 12 OFD Diode Shutdown

CONCLUSIONS

The first space flight cryogenic flexible diode heat pipes were developed and verified under microgravity conditions on the Space Shuttle on STS-94 (July 1997) and the previous, minimum mission STS-83 (March 1997). The heat pipe working fluids were oxygen (with an operating range of about 60 to 145 K) and methane (about 95 to 175 K). The heat pipes were verified as part of the CRYOFD experiment which was a reflight of the HH based Cryogenic Test Bed.

The oxygen and methane heat pipes are .55 and .65 m, long, respectively, with flexible bellow sections of .27 and .4 m and a composite wick. The composite wick (with a fine screen mesh surrounding a coarse wick) provides more than 3.5 times the transport capacity of a homogeneous wick once the pipe is primed. The requirements for the oxygen heat pipe were for minimum transport capacities of 2 W at 60 K and 8 W at 100 K with temperature drops of less than 1 K/W and a diode energy shutdown of less than 1.2 W-hr. The requirements for the methane heat pipe were for minimum transport capacities of 5 W at 100 K with temperature drops of less than 1 K/W and a diode energy shut down of less than 1.3 W-hr. As verified in the STS-94 flight, the heat pipes met and exceeded their requirements with the exception of the oxygen 60 K specification which could not be verified using the CRYOFD's limited net cooling capacity. The demonstrated high transport capabilities verified the operation and benefits of the composite wick design. Overall, the CRYOFD was the first flight of cryogenic flexible diode heat pipes, only approximately the fifth flight of cryogenic heat pipes, and the flight of the highest capacity oxygen and methane fibrous wick heat pipes flown to date.

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REFERENCES

1. Brennan, P., Stouffer, C., Thienel, L., and Morgan, M., "Performance of the Cryogenic Heat Pipe Flight Experiment" SAE Technical Paper Series number 921408, July 1992.
2. Brennan, P., Thienel, L., Swanson, T., and Morgan, M., "Flight Data for the Cryogenic Heat Pipe (CRYOHP) Experiment" AIAA Paper number 93-2735, July 1993.
3. Brennan, P., Thienel, L., "Cryogenic Heat Pipe Technology" NASA/GSFC Capillary Pumped Loop Workshop IV, September 1994.
4. Brennan, P., Thienel, L., Stoyanof, M., Bello, M., "Design and Performance of the Cryogenic Two Phase Flight Experiment" SAE Technical Paper Series number 941474, June 1994.
5. Thienel, L., Stouffer, C., Brennan, P., "The Cryogenic Test Bed, A Discussion of Techniques Used and Lessons Learned Through Two Shuttle Flights (STS-53 and STS-62)" 1st Annual Spacecraft Thermal Control Symposium, 16 - 18 November 1994, Albuquerque, New Mexico.
6. Thienel, L., and Stouffer, C., "The Cryogenic Test Bed Experiments" NASA Technical Conference Publication 3310, 1995 Shuttle Small Payloads Symposium, September 1995.
7. Rosenfeld, J., Wolf, D., Buchko, M., and Brennan, P., "A Supercritical Start-up Limit to Cryogenic Heat Pipes in Microgravity" Proceedings from the IX International Heat Pipe Conference, pp. 742-753, 1-5 May 1995, Albuquerque, New Mexico.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

°C	Degrees Celsius
AFRL	Air Force Research Laboratory
BETSU	Brilliant Eyes Thermal Storage Unit
CECM	CTB Experiment Control Module
CFDHP	Cryogenic Flexible Diode Heat Pipe
CRYOFD	Cryogenic Flexible Diode Heat Pipe Flight Experiment
CRYOTP	Cryogenic Two Phase Flight Experiment
CTB	Cryogenic Test Bed
CTE	Coefficient of Thermal Expansion
GSFC	Goddard Space Flight Center
HH	Hitchhiker
hr	Hour(s)
HPSS	Heat Pipe Support Structure
J&T	Jackson and Tull
K	Kelvin(s)
m	Meters
MDP	Maximum Design Pressure
MFD	Methane Flexible Diode Heat Pipe
MLI	Multi-Layer Insulation
OAST	Office of Advanced Science and Technology
OFD	Oxygen Flexible Diode Heat Pipe
PCM	Phase Change Material
PDB	Power Distribution Box
PRT	Platinum Resistance Thermometer
SAI	Swales Aerospace, Inc.
SS	Stainless Steel
SS	Steady State
STP	Space Test Program
STS	Space Transportation System (Shuttle)
TSU	Thermal Storage Unit
UEP	Upper End Plate
W	Watt(s)

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